Counterflow Drag Reduction Studies for a Blunt Cone in High Enthalpy Flow

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Abstract
Drag reduction by counterflow supersonic jet for a 60-degree apex angle blunt cone in high enthalpy flow is investigated in a free piston driven hypersonic shock tunnel, HST3. For flow Mach number of 8 with specific flow enthalpy of 5 MJ/kg, it has been observed that the drag force decreases with increase in the ratio of supersonic jet total pressure to the freestream pitot pressure until the critical injection pressure ratio is reached. Maximum percentage drag reduction of 44 is measured at the critical injection pressure ratio of 22.36. Further increase in injection pressure ratio has reduced the percentage drag reduction. Experimentally obtained drag signals portray the change in nature of the flowfield, around the model, across the critical injection pressure ratio.

Keywords: Hypersonic flow, drag reduction and free piston shock tunnel

1. INTRODUCTION

High heat load on hypersonic vehicles has put constraints on aerodynamicists to modify the vehicle shape to lessen the heating rates encountered in hypersonic flight. One suggested modification for the hypersonic vehicles is to provide bluntness at the nose of the vehicle. Although this alteration reduces surface heat transfer rate, drag force experienced by the vehicle increases. Therefore this drag penalty has become the prime concern of aerodynamicists and various drag reduction technologies [1-5] are the outcome of it. Among all these methods, injection of supersonic jet from the stagnation point to alter the flowfield ahead of the nose is an interesting method to reduce the wave drag. Finley [6] conducted experiments to study the effect of injection and reduction in pressure coefficient at Mach number 2.5. Modifications in the flow field, in the presence of a forward facing jet or plasma, have also been reported [7]. All these counterflow drag reduction (CDR) studies have been carried out either at lower enthalpies in shock tunnel or at low Mach numbers and low enthalpies in wind tunnels. Apart from this, in most of these investigations, observation based inferences are made for prediction of flowfield around the test configuration. Therefore after successful establishment of free piston driven shock tunnel, HST3, much attention has been given to the CDR studies at higher Mach number and at higher enthalpy [8] to capture the actual flow physics through measurements for various jet total pressures. Thus measurement-based prediction of the flowfield is the central thought of these investigations. Therefore, a 60-apex angle blunt cone model integrated with the accelerometer force balance is employed for CDR experiments in free piston driven shock tunnel. A solenoid-based injector is developed and used for injection of supersonic jet. Details of the experiments and results along with the test model and force balance are given in the following sections.

2. EXPERIMENTAL FACILITY

Experimental results reported here are carried out in the newly established free piston driven shock tunnel, HST3. The HST3 tunnel, shown schematically in Fig. 1, is of moderate size having a piston weight of 20 kg. The tunnel consists of a 10 m long 165 mm internal diameter compression tube, 4.4 m long 39 mm diameter shock tube, a convergent-divergent Mach 8 conical nozzle and 2 m long 1 m

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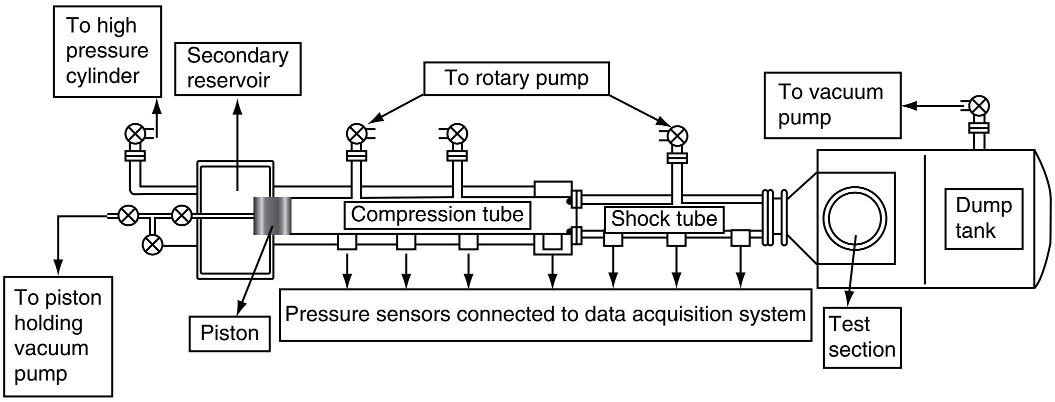

Figure 1. Schematic diagram of the fully instrumented free piston driven hypersonic shock tunnel HST3.

diameter size test section cum dump tank. The piston is driven by nitrogen gas in 1 m long 500 mm diameter reservoir and the compression tube is filled with helium gas at 1 atm pressure. The compression tube is provided with sensors at four locations to measure the acceleration and speed of the piston during the run. A pressure transducer is mounted at the end of the compression tube to monitor the compression tube pressure. The shock tube has two pressure sensors mounted known distance apart towards the end to monitor the shock speed and one pressure transducer at the end of the tube to measure the stagnation pressure at the entry of the nozzle. The tunnel has been calibrated for stagnation enthalpy of about 5 MJ/kg. The flow quality and uniformity inside the test section is checked using the pitot rake on a traverse mechanism. The performance of the tunnel is estimated using different numerical codes based on the measured pitot signals and typical tunnel operating parameters. The freestream conditions of the tunnel are listed in Table 1.

A 60-degree apex angle blunt cone model of base diameter 70 mm is used for the drag force measurement during the CDR studies. This 0.4 kg model is fabricated using an aluminum alloy. A 2 mm diameter orifice is made at the stagnation point for the jet injection experiments. Connection of the orifice with the gas reservoir is made using the flexible tubing. Provision is also made inside the model for integration of the force balance. The schematic of the test model with the force balance is shown in Fig. 2. The balance system consists of two rubber bushes with a central sting attached to the model through two metallic rings. The model moves freely during the test time as the resistance offered by the rubber bushes during the run time is negligible [9]. The miniature accelerometer (PCB 303 A 20849; 10 mV/g sensitivity) is mounted inside the model along its axis to measure the acceleration experienced by the model during the hypersonic flow in the test section. The dynamic calibration of the force balance has been accomplished using the impulse hammer test. The impulse of known value and the corresponding acceleration of the model are used to arrive at the proper impulse response function.

A solenoid-based gas injector is fabricated and used to synchronize the injection of supersonic jet with the entry of hypersonic flow in the test section. An electronic controller for this injector is designed and developed to supply 24 V power to the solenoid valve during the experiments. Inlet of the injector

Table 1. Free stream conditions in the free piston driven hypersonic shock tunnel HST3

Freestream static pressure (P_∞)	0.284 kPa
Freestream static temperature (T_∞)	316 K
Freestream Mach number (M_∞)	~8.0
Freestream stagnation enthalpy (H_0)	~5.0 MJ/kg

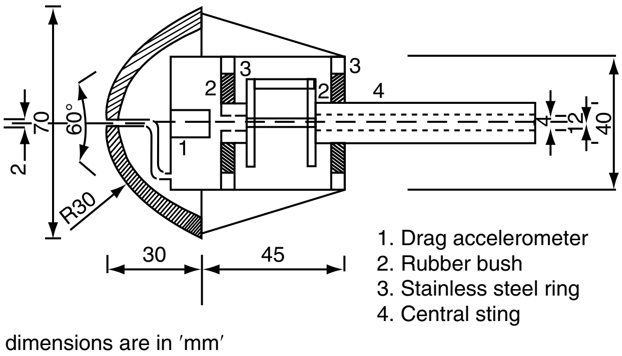

Figure 2. Schematic diagram of the 60-degree apex angle blunt cone with the accelerometer based balance system and passage for supersonic jet injection at the stagnation point.

is connected to the high-pressure cylinder while outlet is connected to orifice of the test model. High-pressure cylinder is provided with the regulator to alter the total pressure of supersonic jet to carry out injection experiments at various injection pressure ratios, P_{0j}/P_{02}, where P_{0j} is total pressure of jet and P_{02} is pitot pressure of high enthalpy hypersonic flow.

3. EXPERIMENTAL STUDIES

The 60-degree apex angle blunt cone model is mounted at zero degree angle of incidence in the test section of HST3. Experiments without and with injection of supersonic jet of different pressure ratios are conducted for the calibrated freestream conditions. Before conducting the experiments for drag reduction studies, the reaction force on the model due to the supersonic jet emerging from the orifice was measured in absence of hypersonic flow in the test section. For these 'dry runs' (experiment without hypersonic flow in test section), the model along with accelerometer balance system was mounted in the test section where pressure was maintained at the level equivalent to the pitot pressure of Mach 8 freestream flow. The solenoid controller was manually triggered and emergence of supersonic jet from the orifice at the stagnation point of the model was ensured. The reaction force on the model due to the emergence of supersonic jet was measured by the drag accelerometer in absence of test gas flow. These measurements have shown that the drag force on the test model, induced by the supersonic jet, is negligible and is below the sensitivity level of the accelerometer. Hence the jet induced drag is neglected in the experimental data presented here.

During the actual experiments with supersonic jet injection, trigger pulse to the solenoid controller is given from the pressure transducer mounted at the end of compression tube. The trigger voltage is adjusted in such a way that the injection of supersonic jet synchronizes with the arrival of hypersonic flow in the test section. Experiments for different injection pressure ratios 7.45, 14.91, 22.36, 29.82 and 37.27 are carried out for the same freestream conditions by varying the total pressure of the supersonic jet. Acceleration of the model is recorded for all the test cases. Consistency in the acceleration signal, for each test case, has been observed.

4. RESULTS AND DISCUSSION

Experimentally obtained acceleration signal and the system response function are used to recover the drag force for the experiments without injection. Nature of thus obtained force signal is found similar to the pitot signal where flow establishment time and steady flow test time are clearly seen (Fig. 3). Drag coefficient is calculated from the recovered drag signal. Experimentally obtained drag coefficient for the blunt cone model is 0.61 while the corresponding theoretically [10] calculated drag coefficient is 0.63.

Drag force for injection experiments is recovered from the acceleration signal with the help of same transfer function used for experiments without injection. Reduction in drag force in the presence of supersonic jet has been observed for all the injection pressure ratios. The mechanism for this drag

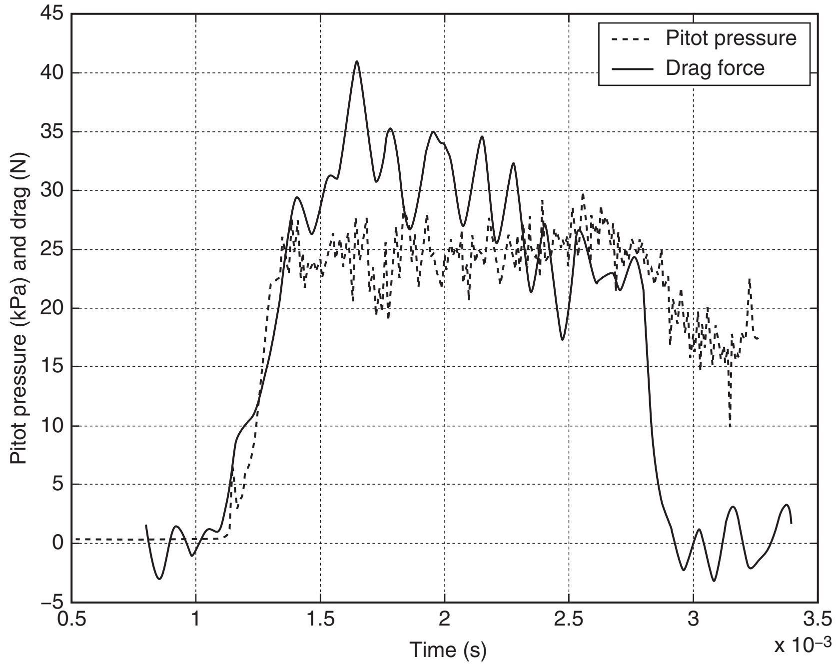

Figure 3. Variation of drag signal along with the pitot pressure in the test section.

reduction lies in the interaction of supersonic jet and oncoming hypersonic flow. The jet emanating from the blunt body interacts with the oncoming hypersonic flow causing the bow shock wave to stand away from the model surface by forming a fluidic spike mounted at the stagnation point of the blunt cone model. During the process of interaction with the hypersonic flow, jet flow forms a cell structure which ends with a terminal shock to meet the pitot pressure of the hypersonic flow at the stagnation point. This stagnation point is called as 'floating stagnation point' since in the unsteady interaction of the jet and oncoming hypersonic flow, this stagnation point oscillates along the central body axis. After interaction with the oncoming hypersonic flow, fluid from the jet deflects out and flows back till it reattaches the blunt body. In this flow path, fluid from the jet forms toroidal recirculation region. Interaction of the jet and hypersonic flow is clearly shown in Fig. 4. The wave drag reduction for the counterflow supersonic jet is derived from both the splitting of a single strong shock into multiple shock waves and replacing the blunt body by a slender equivalent body. The measured variation of drag coefficient with injection pressure ratio is shown in Fig. 5 while Fig. 6 shows the percentage drag reduction for those injection pressure ratios. Maximum reduction in the drag force corresponds to the injection pressure ratio 22.36.

It is clear from the Fig. 5 that the drag force decreases with increase in injection pressure ratio. However, this decrease continues till the drag reduction reaches its maximum value at the injection pressure ratio 22.36. This pressure ratio corresponding to the maximum drag reduction is termed as 'critical pressure ratio'. Percentage reduction in drag coefficient decreases with further increase in injection pressure ratio above the critical value. Therefore two distinguished flow regimes have been observed, for the first time, during the drag reduction studies in the free piston driven shock tunnel. This change in nature of the percentage of drag reduction across the critical injection pressure ratio is attributed to the change in nature of the flowfield around the model, which has been observed in the force signals during the force measurements. Finely [6], from his flow visualization studies, also reported similar change in nature of the flowfield, where it had been observed that the multi celled unsteady counterflow supersonic jet structure collapses to single celled steady supersonic jet structure after

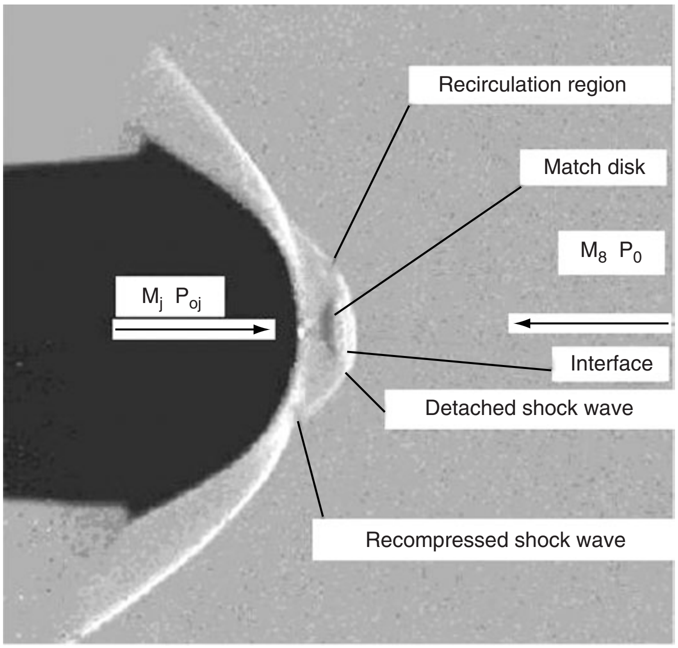

Figure 4. Typical schlieren picture of flow features of hypersonic flow over the blunt cone with an opposing supersonic jet[2].

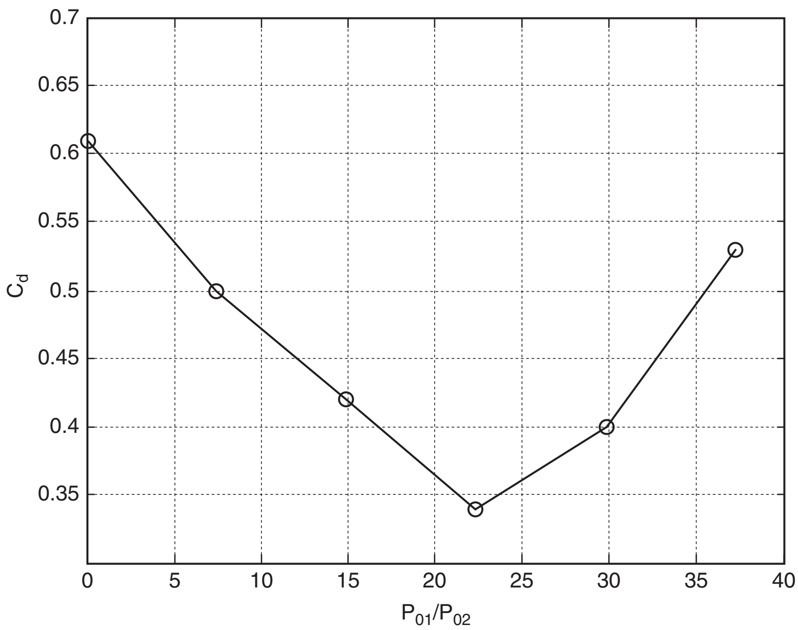

Figure 5. Variation of drag coefficient with the pressure ratio of the forward facing supersonic jet.

critical point of injection. Unsteadiness observed in the drag force, during the experiments, for typical injection pressure ratios up to the critical value, is shown in Fig. 7 while Fig. 8 shows the steadiness of the drag force for typical injection pressure ratios higher than the critical value. Undulations observed in the drag signal for the experiments with and without injection are attributed to the accelerometer

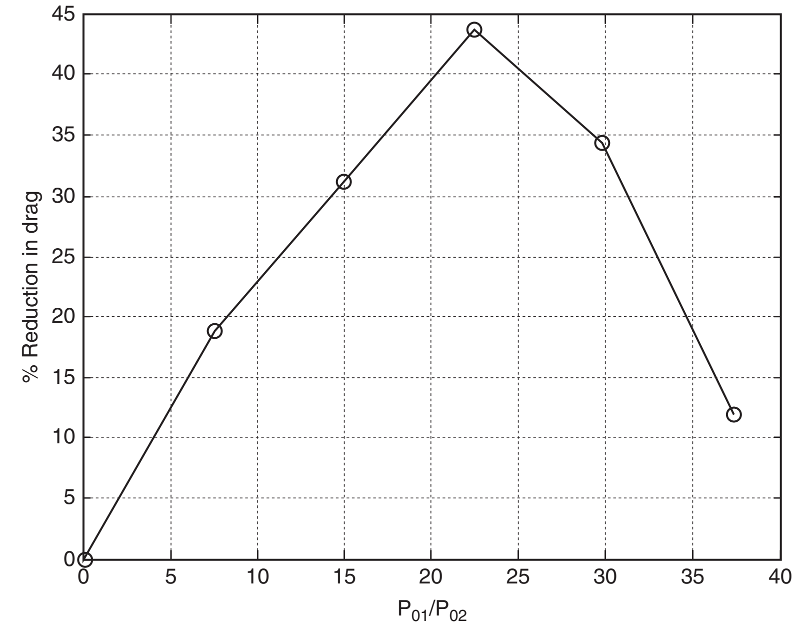

Figure 6. Variation of percentage drag reduction with the pressure ratio of the forward facing supersonic jet.

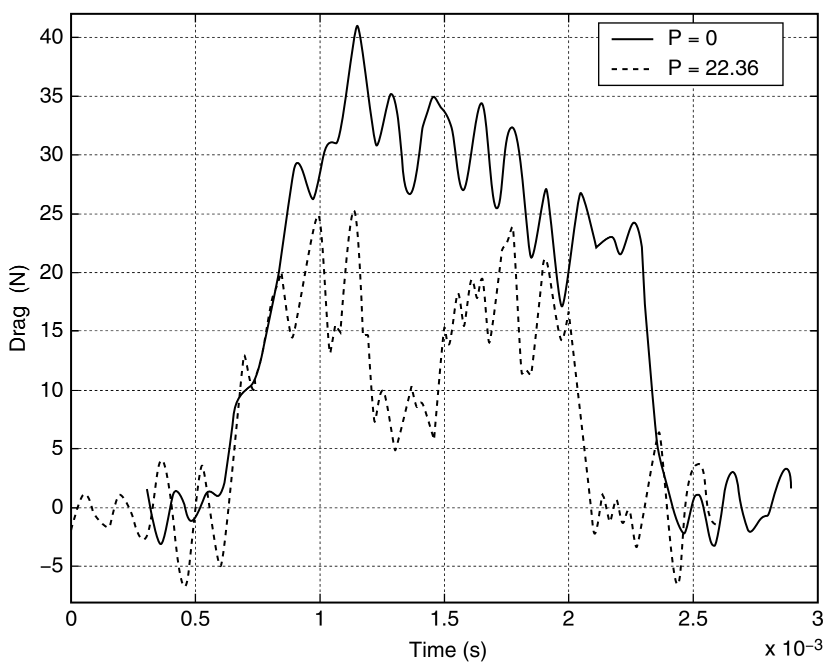

Figure 7. Experimentally observed unsteadiness in the drag signal for injection pressure ratios up to the critical value.

property however the gross unsteadiness is evident in Fig. 7 where drag force value drops by around 60% at ~1.3 ms and again regain its original magnitude at ~1.5 ms. Such a trend is missing in Fig. 8 which clearly demonstrates the steadiness. Efforts are in progress for the quantification of the unsteadiness and governing parameters for the same.

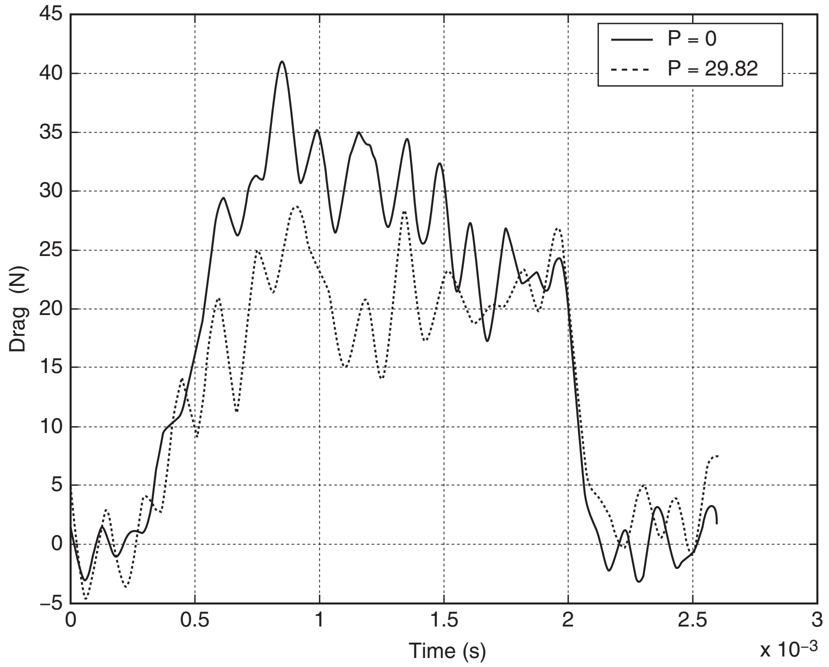

Figure 8. Experimentally observed steadiness in the drag signal for injection pressure ratios higher than the critical value.

5. CONCLUSION

Experiments for CDR are conducted with a 60-degree apex angle blunt cone model integrated with the accelerometer force balance. Experiments with supersonic jet injection are carried out for five injection pressure ratios by varying the total pressure of the jet. Maximum reduction in the drag force of 44% is recorded for the critical injection pressure ratio of 22.36. Change in observed nature of the percentage drag reduction is attributed to the change in nature of the flow across the critical injection pressure ratio, which has been captured for the first time during measurements.

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